Radiative corrections to $e^+e^- \to \pi^+\pi^-\gamma$

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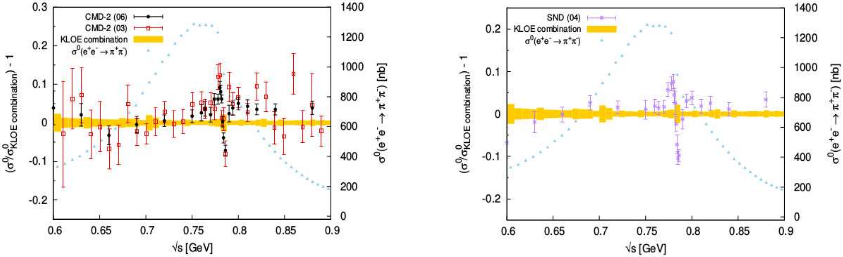
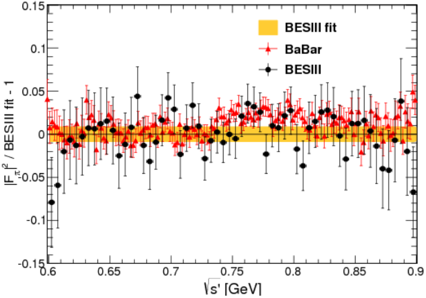
Outline

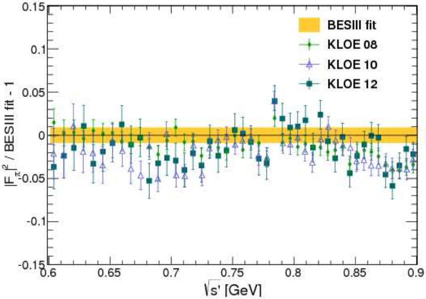
KLOE, CMD-2 and SND measurements



A. Anastasi *et al.* [KLOE-2 Collaboration], JHEP **1803** (2018) 173

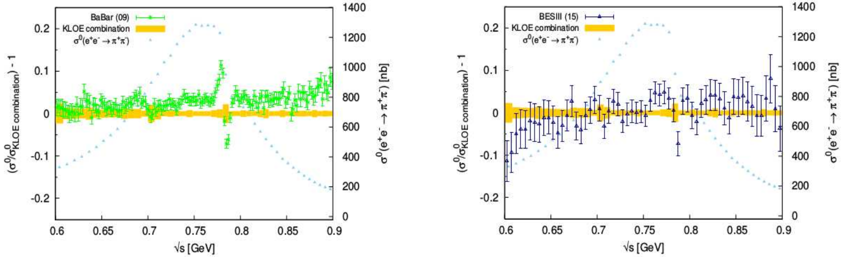
BaBar, BES and KLOE measurements





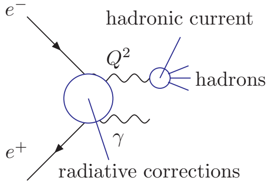
M. Ablikim *et al.* [BESIII Collaboration], Phys. Lett. B **753** (2016) 629

BaBar, BES and KLOE measurements



A. Anastasi *et al.* [KLOE-2 Collaboration], JHEP **1803** (2018) 173

$$d\sigma(e^+e^- \to hadrons+\gamma_{isr}) = H(Q^2,\theta_\gamma)d\sigma(e^+e^- \to hadrons)(Q^2)$$



- measurement of $R(s)$ over the wide range of energies, from threshold up to $\sqrt{s}$
- large luminosity from factories compensate α/π from photon radiation
- precise measurement involves radiative corrections
- FSR contribution has to be subtracted
- Monte Carlo generators needed (Phokhara)

Phokhara Monte Carlo generator

PHOKHARA 9.3:

$\pi^+\pi^-$, $\mu^+\mu^-$, 4π, $\bar{N}N$, 3π, KK, $\Lambda\bar{\Lambda}$, $P\gamma$,

J/ψ, $\psi(2s)$, χ_{c_1}, χ_{c_2}

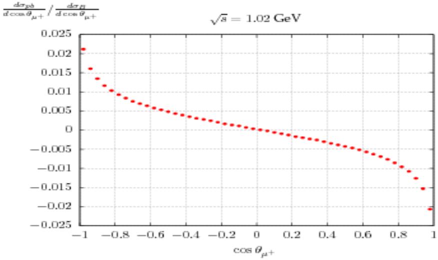
-ISR at NLO: virtual corrections to one photon events and two photon emission at tree level

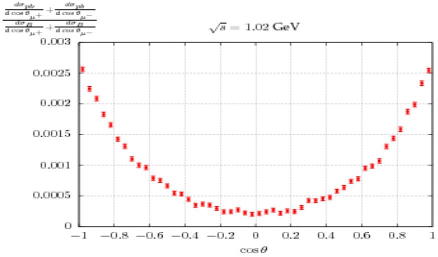
-FSR at NLO: $\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-, $\bar{p}p$

-tagged or untagged photon

-ISR at NNLO for $\mathbf{e^+e^-} \to$ **hadrons (muons)**

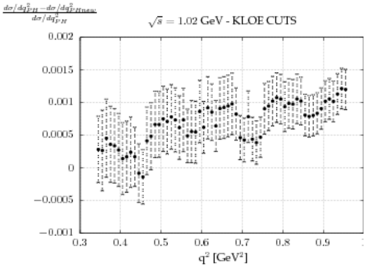
NLO corrections for $e^+e^- \to \mu^+\mu^-\gamma$

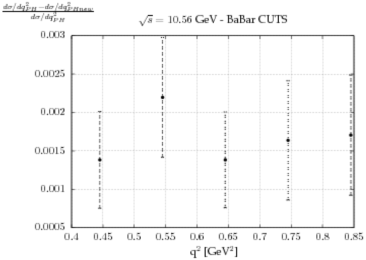




F. Campanario, H. Czyż, J. Gluza, M. Gunia, T. Riemann, G. Rodrigo and V. Yundin, JHEP **1402** (2014) 114,[arXiv:1312.3610 [hep-ph]].

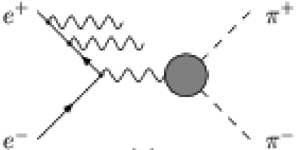
NLO corrections for $e^+e^- \to \mu^+\mu^-\gamma$



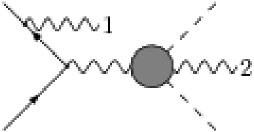


F. Campanario, H. Czyż, J. Gluza, M. Gunia, T. Riemann, G. Rodrigo and V. Yundin, JHEP **1402** (2014) 114,[arXiv:1312.3610 [hep-ph]].

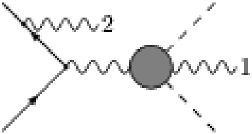
Two photons emission



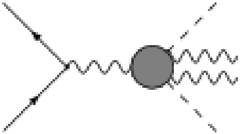
(a)



(b)

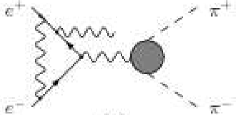


(c)

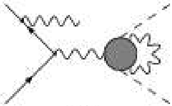


(d)

Virtual corrections



(a)



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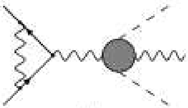

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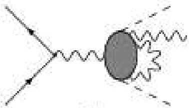
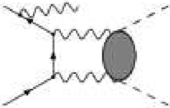
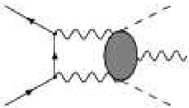


(d)



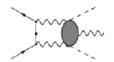
(e)



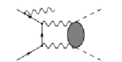
(f)

Modeling pion - photon interaction

-Factorization of the form factor:



$$= \quad \mathbf{F_\pi(s) \times sQED}$$



$$= \quad \mathbf{F_\pi(q^2) \times sQED}$$

-Real emission proportional to the form factor

-Form factor:

$$F_\pi(q^2) = \sum_n c^{\pi}_{\rho_n} BW_{\rho_n}(q^2)$$

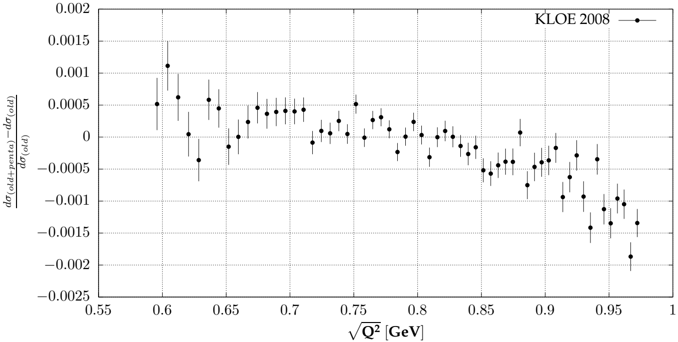
-Renormalizable model

H. Czyz, A. Grzelinska and J. H. Kuhn, Phys. Rev. D **81** (2010) 094014

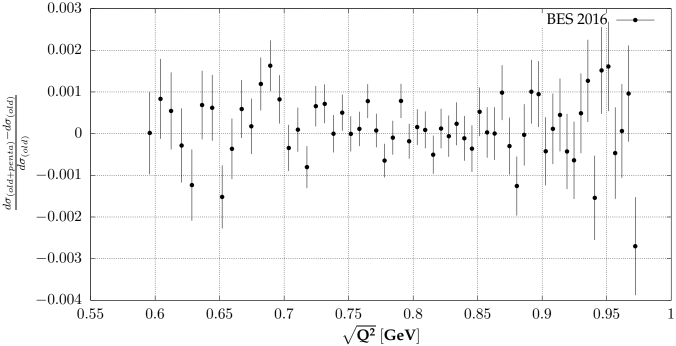
Tests of the code

- check of the scalar integrals using few different libraries (QCDLOOP, LoopTools)
- comparison of two independent codes
- check the stability of the code (soft, collinear limit) - agreement at the level 10^{-5}
- test for the independence on the separation parameter between soft and hard part (below 1 ‰)
- cancelation of infrared divergences between soft and virtual part
- gauge invariance

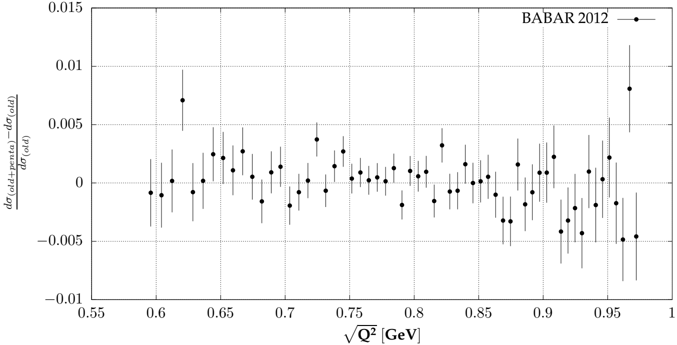
- $\sqrt{s} = 1.02$ GeV
- Pion tracks: $50^o < \theta_{\pi^\pm} < 130^o$, $|p_{z_{\pi^\pm}}| > 90$ MeV
- Missing photon angle: $|\cos\theta_\gamma| > \cos 15^o$
- Track mass: $m_{trk} > 130$ MeV
- $q^2 \in (0.35, 0.95)$



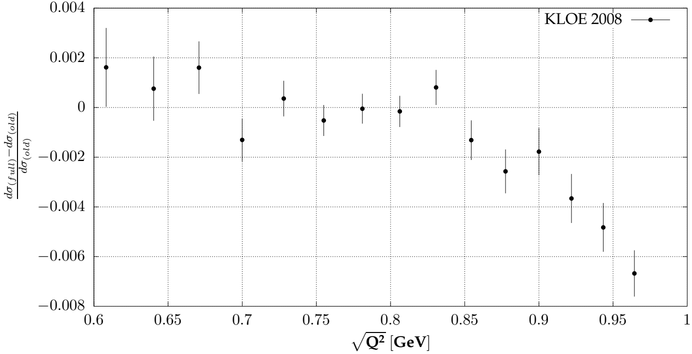
- $\sqrt{s} = 3.773$ GeV
- Pion tracks: $22.9^o < \theta_{\pi^\pm} < 157.1^o$, $|p_{T_{\pi^\pm}}| > 300$ MeV
- Minimal photon energy: $E_\gamma > 400$ MeV
- Missing photon angle: $|\cos\theta_\gamma| < 0.8$ or $0.86 < |\cos\theta_\gamma| < 0.92$
- $q^2 \in (0.35, 0.95)$



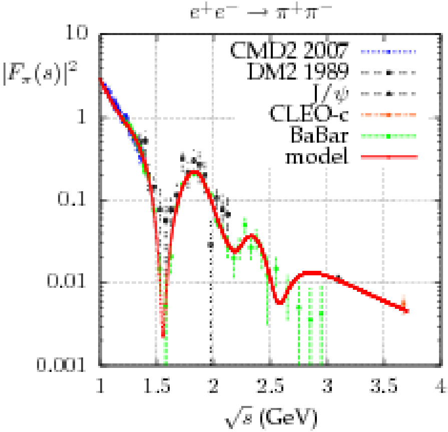
- $\sqrt{s} = 10.56$ GeV
- Pion tracks: $20^o < \theta_{\pi^\pm} < 160^o$, $|p_{T_{\pi^\pm}}| > 300$ MeV
- Minimal photon energy: $E_\gamma > 3$ GeV
- Missing photon angle: $20^o < \theta_\gamma < 160^o$
- $|q_1| > 1$ GeV (π^-) and $|q_2| > 1$ GeV (π^+)
- $q^2 \in (0.35, 0.95)$



Leading logarithmic approximation for virtual FSR corrections



Pion form factor



H. Czyz, A. Grzelinska and J. H. Kuhn, Phys. Rev. D **81** (2010) 094014

Conclusions

- The size of the pentabox contribution is too small to be able to explain discrepancies between KLOE and BABAR data.
- For KLOE experiment missing virtual FSR corrections may be non negligible but small
- For BaBar and BES experiment virtual FSR corrections are small due to the behavior of the form factor

Forthcoming developments

- Implementation of the radiative corrections to initial states at two-loop level for the process $e^+e^- \to$ hadrons $+\gamma$ using leading logarithmic approximation